Wind Power Generator Design

for the DC House Project

A Senior Project

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Bachelor of Science

by

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Abstract

The purpose of this project is to introduce a cost efficient alternative in converting wind into energy for third world countries. Currently there are approximately 1.6 billion people who have limited access to electricity. As part of the DC House project, we hope to develop a solution for them as the use of electricity is becoming an essential part of life. One of the natural energy resources to provide power to the DC House is wind. The components used for the project are a DC motor and DC-DC converter to translate wind into power and produce DC voltage and current, with the output being 24V DC. In testing this system, a variable speed drive and electronic load were used to simulate wind speeds and loads by adjusting RPM speeds of the motor and controlling the amount of current outputted by the boost converter. In addition to regulating the output voltage and current, we also monitored the output power and efficiency of the system. We observed the efficiency of the system to be estimated at 80% when the motor is operating at medium to high speeds, 300-600 RPM. However, the maximum output power of our proposed system is approximately 24W at 600RPM. This is due to the limited amount of current that the system is outputting, which is less than 1A for speeds at or less than 600RPM. Due to these results, the current system is not effective for the proposed use, but can be improved to become of use. One suggestion, should this system be used again, is to implement the use of gears onto the motor to generate faster speeds for it to run, thus allowing more current to be created.

Chapter I. Introduction

Wind is a source of energy that can be formed in any type of space. “On Earth, it is formed by the movement of air” [6]. In scientific terms, wind is the flow of gases that move from an area of high pressure to an area of low pressure. Winds are commonly classified by their spatial scale (length, areas, distance, and size), speed, force, location, cause of generation, and effect. The classification of wind is highly unpredictable since it is also dependent on weather. Regardless of the unpredictability of wind, it can be considered a very efficient and beneficial source of natural energy. For one, wind is very a resourceful and environmentally friendly type of energy that can be used as a replacement of other polluting energy sources like power plants. Wind is also an inexhaustible type of energy which will continue to be available and plentiful when other sources of energy like coal and oil have been depleted.

Wind power has been used for the past hundreds of years, starting with the creation of the sail boat, which had an impact on the later development of sail-type windmills. The completion of the windmill sail invention influenced the performance and design of modern wind turbine blades. Specifications for wind turbine blades are “1) camber along the leading edge, 2) placement of the blade spar at the quarter chord position (25% of the way back from the leading edge toward the trailing edge), 3) center of gravity at the same ½ chord position, and 4) nonlinear twist of the blade from root to tip” [2]. The first windmills were developed in Persia around 500-900 A.D., and the purpose of the windmills were to grind grain and pump water to help with harvesting. The initial, “most important application of windmills at the subsistence level was for mechanical water pumping using relatively small systems” [2].

“The first use of a large windmill to generate electricity was a system build in Cleveland, Ohio, in 1888 by Charles F. Brush” [2]. The invention is called the Brush machine and it operated using a low-speed, high-solidity rotor. Throughout history there have been many types of designs for the rotor and blade configuration that were tested and “found to be inadequate for generating appreciable amounts of electricity” [2]. But with the involvement of the federal government in the research and development of wind energy, there have been better and more effective studies and results in the production of turbines that would be used to generate large scales of electricity. Now there are major technological developments that have been made which enable wind power commercialization, and these developments will help in demonstrating that wind energy will be the most cost effective source of electrical power and therefore is the way of the future.

In this project, we are designing a wind power system that consists of turbine blades, a permanent magnet motor, and a Boost-Buck (also known as Cuk) DC-DC converter. This system will be used as one of the main sources for the DC House that is currently being developed at California Polytechnic State University, San Luis Obispo (Cal Poly SLO).

Chapter II. Background

As technology continues to advance and improve in today's world, and the world's population growth expecting to increase, the demand for electricity will rise and become more vital to human life. According to Anup Shah, in 2005 "a quarter of humanity currently lives without electricity" and from the Population Reference Bureau, we expect population to grow only in less developed countries, which we expect will increases the amount of people that will not have electricity available to them [1][3]. Due to these facts, we want to propose an idea of the DC House that will provide a solution for the population that does not have access to electricity. The DC House will only use renewable energy sources to supply power and energy in an environmental friendly manner.

The DC House project was created to develop effective methods of distributing power to the "estimated 1.6 billion people" who are presently without electricity and "whom are either on or below the poverty line" [5]. This project is only the first step towards creating designs of renewable power using wind, solar, hydro, and human generated energy for people in less privileged areas. The purpose for using renewable energy sources to power up the DC house is to utilize the natural resources that are available around the world. These four different types of energy resources are essential for the project because some locations are limited to what the environment can allow them to use. Further development of this project will be made by companies and organizations that will have interest in the growth of the entire world.

One of the main sources for the development of the DC House is wind energy. Wind energy is widely available as wind occurs everywhere around the world. The goal of the Wind Power Generator Design project is to research and design a method of efficiently using wind as an alternative energy source. This project is only a section of a larger project called the DC House project. The DC House project will be using renewable energy sources to provide dc power to houses in areas that are underdeveloped with respect to social, political, and economic divisions. Using dc power will make the project more cost efficient and applicable for the less fortunate people since its directly providing power to the houses without the need of dc to ac conversion.

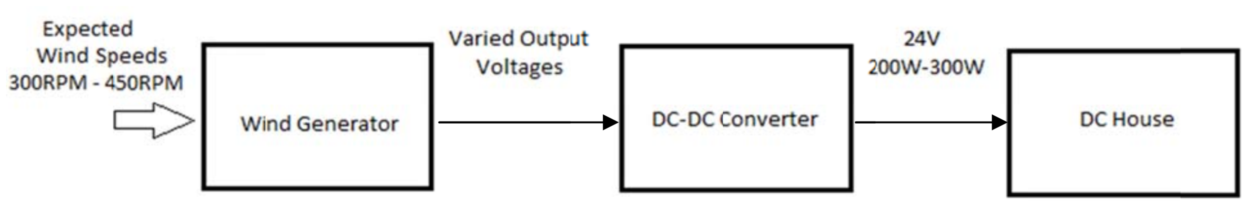
Chapter III. Requirements

Although wind is a limitless source of energy, it is unstable and unpredictable due to its constant change in its characteristics. The Wind Power Generator Design needs to provide a constant output voltage of 24V with an output power of 200-300W, in order to operate basic necessities in a house. The design must also be cost efficient, portable, and be able to produce electricity consistently.

The DC House project is aimed towards underdeveloped countries that don't have sufficient funds to buy expensive power systems, such as power plants. Due to this, the wind energy product must be cost efficient so they can afford it and have access to electricity at a low price. Since the DC House as a whole needs to be inexpensive, the price of the Wind Generator needs to be in the range of $300-500. This price includes the following components: turbine blades, permanent magnet motor, and a DC-DC converter. Other components that will also be necessary for this design will depend upon the location of use, such as the height of a stand to hold the generator for maximum production.

The size of the generator must also be considered when designing this project. Since the main target of consumers are people in third world countries, the product must be portable and easy to install due to their lack of resources. Considering the different weather conditions that can occur, the generator must be able to be repositioned in order to obtain optimal production of wind.

In addition, we also need to be able to produce electricity consistently. In order to achieve this goal, it is necessary for us to include a DC-DC converter into our system that outputs 24V and 200-300W. This DC-DC converter needs to withstand the output power rating at or above 200W so the converter will not burn out and malfunction. When researching for the converter, it was determined that the cost of all the components necessary to assemble the converter ourselves will almost be equivalent to the cost of purchasing a DC-DC converter from a manufacturer. It is also more reliable to purchase from a manufacturer than to manually assemble it since the customer we are designing this for may not have the equipment and experience to build one. Figure 3-1 shows the block diagram of the proposed system.



Chapter IV. Design

The main goal of the Wind Generator project is to create a system that converts wind into energy to produce power to the DC house. In order to achieve this goal, the system needs to comprise the following components: turbine blades, DC motor, tower for the motor, and a converter. The overall wind system should ideally resemble Figure 4-1, as shown below.

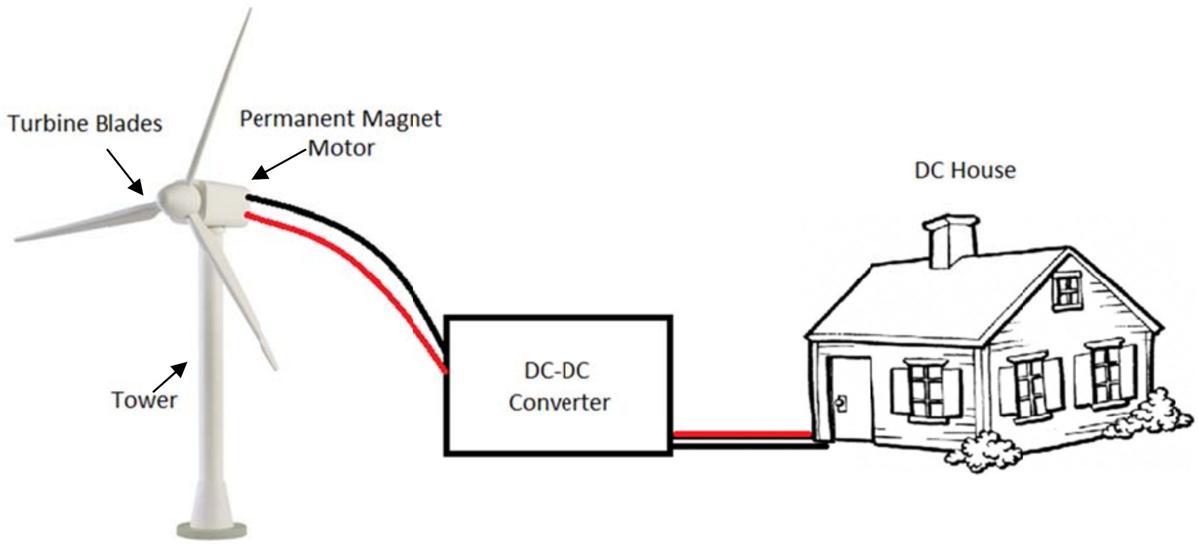


Figure 4-1: Ideal Wind Generator System

The turbine blades are necessary to convert the wind speed into torque to permit the permanent magnet motor to spin and ultimately allow the motor to become a generator and source of energy. To obtain maximum amount of wind speed, it has been determined through research that a three-blade system will be most efficient. The reason is due to the speed-to-torque conversion for if the turbine blades comprise of more than three, the speed of the blades may be fast but may not apply enough torque to turn the motor to create sufficient amounts of voltage and current. However, if the blade system has less than three blades, there may not be strong enough winds going through the turbine blades to create adequate amounts of spinning of the blades and turning of the motor.

The length of the tower is essential for allowing the turbine blades to gather the maximum amount of wind speed throughout the entire day. But there are variations to the size of the stand based on the location and environment that the stand is being positioned. Therefore it is difficult to determine the necessary height of the stand without knowing complete details of the environment and the supplementary components of the project.

There are a variety of DC motors that are suitable for creating wind generators. The important aspects that are needed for this project are high output power, high voltage-RPM ratio, and cost efficient. In taking account of wind speeds and also with the requirement of the project being cost-efficient, it is difficult for a motor to output 200-300W; therefore requirements were changed to output 100W for greater feasibility. With this change of providing at least 100W, the motor that we choose must have an upper limit much greater than this amount to prevent stress and risk of damaging the motor**.** Also, we want high voltage-RPM ratio to be able to obtain a reasonable amount of voltage for ideal wind speeds. Therefore, we should be able to output reasonable amount of voltage from the motor at a typical range of RPM and wind speeds. We found that the minimum voltage-RPM ratio is 0.035 and if the motor's ratio is calculated to be less than that, then the motor will be insufficient [3]. In addition, price must also be considered in this project because the aim is towards third world countries that are limited with their budget. With all these considered, a McMillan permanent magnet motor found on eBay seems to be a good candidate for this project given its specifications. The McMillan motor is rated at 2.25HP or 1677W and has a voltage-RPM of 0.051, both of which are capable of providing what is necessary. The following picture shows the specifications of the McMillan motor.

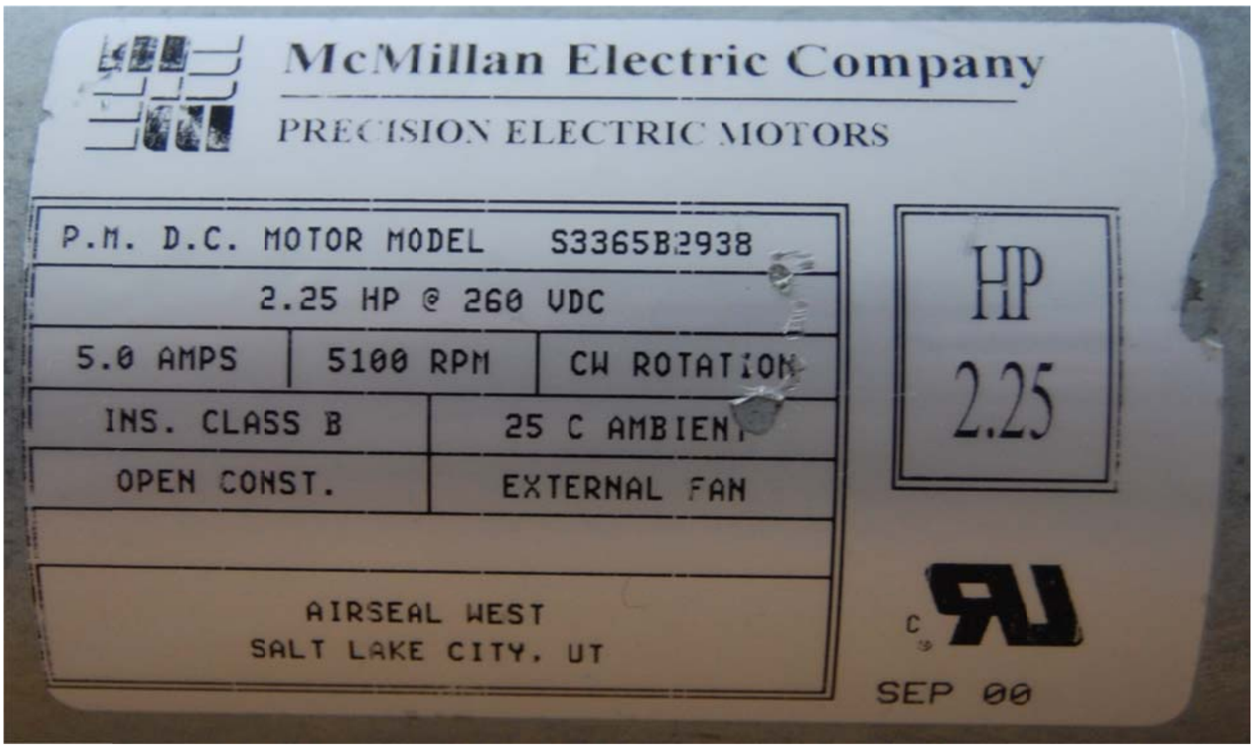


Figure 4-2: Specifications of the McMillan Permanent Magnet DC Motor

The amount of voltage required for the DC house is 24V but the motor can only output smaller amounts of voltage due to the RPM created by typical wind speeds. To increase the voltage output from the motor to 24V, a boost converter is needed. Depending on the boost converter, there are different ranges of input necessary to provide the desired output. Ideally, the best converter to use for a wind generator in this project is one that can obtain a 24V output at extremely low input voltages since wind is inconsistent, varies throughout the day, and also provides speed lower than 1000RPM under normal weather. However, it is difficult to find a converter that has these specifications, can withstand high output power, and is low in cost. We chose the Zahn Electronics Boost DC-DC converter shown in Figure 4-3, due to its input range of 10-20V and rated output of 24V. The input voltage range of 10-20V is feasible for this project because wind can realistically achieve these voltage ranges. In addition, the system needs to provide and handle at least 100W and this converter is rated at 300W, thus being able to endure the DC House's required output power without damaging the Boost Converter. Also, comparing this converter to its competitors, the rated output power on this converter is much greater and the price is cheaper for the use of this project. The input voltage range is shorter in the Zahn Electronics Boost converter compared to the others; however, the specified maximum input voltage in this converter exceeds what we expect the motor to generate from the wind.

Figure 4-3: Zahn Electronic's Boost Converter

The following table shows the specifications and price for each converter that was considered. Again, observing the price, rated input voltage, efficiency, and power, the converter by Zahn Electronics is the candidate best fit for the wind generator project.

Table 4-1: DC-DC Converters considered for the Wind Generator

	Zahn Inc. Boost #DCDC12/24/300	Cui Inc VHK200W-Q24-S24	Cincon CHB150W-24S24	Synqor IQ18240HPC7FNRS-G
Rated Input Voltage (V)	12	24	24	18
Input Voltage Range (V)	10 to 20	10 to 36	9 to 36	9 to 36
Rated Output Current (A)	12.5	8.3	6.5	7.5
Output Power (W)	300	200	156	180
Output Voltage (V)	24	24	24	24
Efficiency (%)	93	84	88	82
Price ($)	169	214.51	159.65	319.74

Chapter V. Test Plans

To test this system, the motor and converter that is chosen for this project must be tested in order to extract more knowledge about our components. Before a converter is chosen, we must find and examine the characteristics of the DC motor that is chosen. In order to do this, an adjustable speed drive machine is used to simulate different wind speeds to distinguish how much output voltage the motor can generate for certain speeds. The Baldor adjustable speed drive will be interfaced with an induction motor, which is then coupled to a DC motor. No load test for the DC motor is necessary to establish the full characteristics of the motor and specifications for a DC-DC converter that will be compatible with the motor.

After choosing a DC-DC converter, the converter itself needs to be tested to obtain knowledge of its characteristics and limitations. To extract this data, we need to first and foremost determine the input voltage range the converter can receive that will allow it to output 24V. This will be done by connecting a DC power supply to the Boost converter and measuring the output voltage with no load. The input range will be established as the set of values in between the minimum and maximum value the converter can intake until the output no longer outputs 24V. The test set up should resemble the block diagram shown in Figure 5-1 below with the electronic load set to “OFF.”

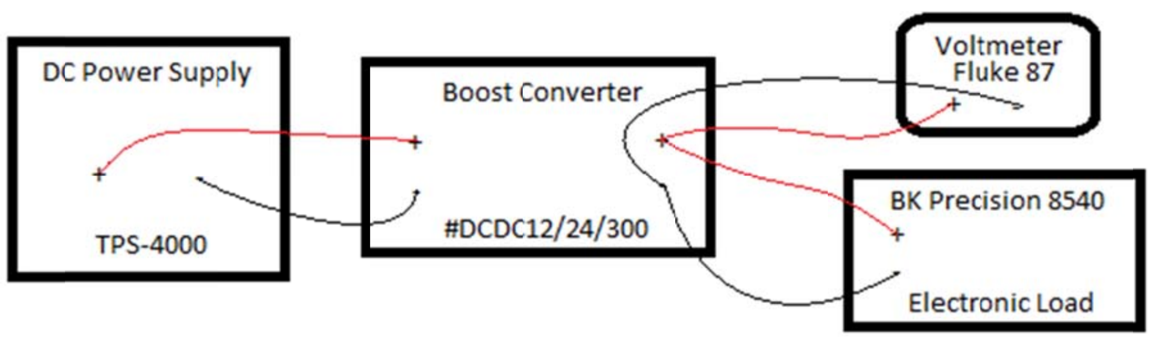


Figure 5-1: Testing the input voltage range of the Boost Converter

It is also important to discover the converter’s efficiency and capability of handling a load. To acquire this information, the converter needs to go through a series of load tests. This is done by using the BK Precision Electronic Load. The Electronic Load will be set to zero to full load, incrementing each load by 10%. Specifically, because this project is interested in generating 100W, the expected amount of current will be the desired output power divided by desired output voltage, which is 4.17A (100W/24V). This value is the amount of current at the full load setting. The experiment will start out at no load (0A) and be increased by 10% of the full load amount until the full load value is reached. Each increase will cause the load to draw more current, allowing us to observe the effects of the converter’s output voltage. This portion of the test will also have the input voltage of Zahn’s Boost converter set at the rated 12V. The circuit should resemble the diagram of Figure 5-1, but instead of using the DC Power Supply TPS-4000, the Hewlett Packard 6574A is used due to its ability to operate at max values of 60V and 35A. The input/output voltages and currents will be recorded during each increment, and will be used to obtain the input and output power of the converter for each increment. Obtaining these values will determine how efficient the Zahn Boost Converter is for this project's application.

Finding the boost converter's line and load regulations are other characteristics we need to examine. Determining the line regulation would allow us to observe how well the converter can maintain its output voltage when the input voltage varies. A low percentage is desired since that would indicate the converter maintains its output voltage close to the desired output of 24V. Testing the converter's load regulation is also desirable for the results will show the converter's ability in maintaining a 24V output while the output power fluctuates.

Having found the DC-DC converter's performance, the next step will be interfacing the motor with the converter. A cart with a torque speed reader and an induction motor will be used to drive the DC motor to simulate wind. A Baldor adjustable speed drive will be used to drive the three phase induction motor, as done during the no load test, allowing us to adjust the speed of the motor to mimic the spin that would be created by the wind. There will be two multimeters connected in between the DC motor and the Boost converter; one multimeter will read the output voltage of the DC motor (input voltage of the Boost converter) while the other multimeter will read the output current of the DC motor (input current of the Boost converter). The output of the boost converter will then be attached to the input of the Electronic Load, the same one used for the individual testing of the boost converter. The overall block diagram for this set up is shown in Figure 5-2. Figure 5-3 shows an actual image of the block diagram schematic for the project from Figure 5-2.

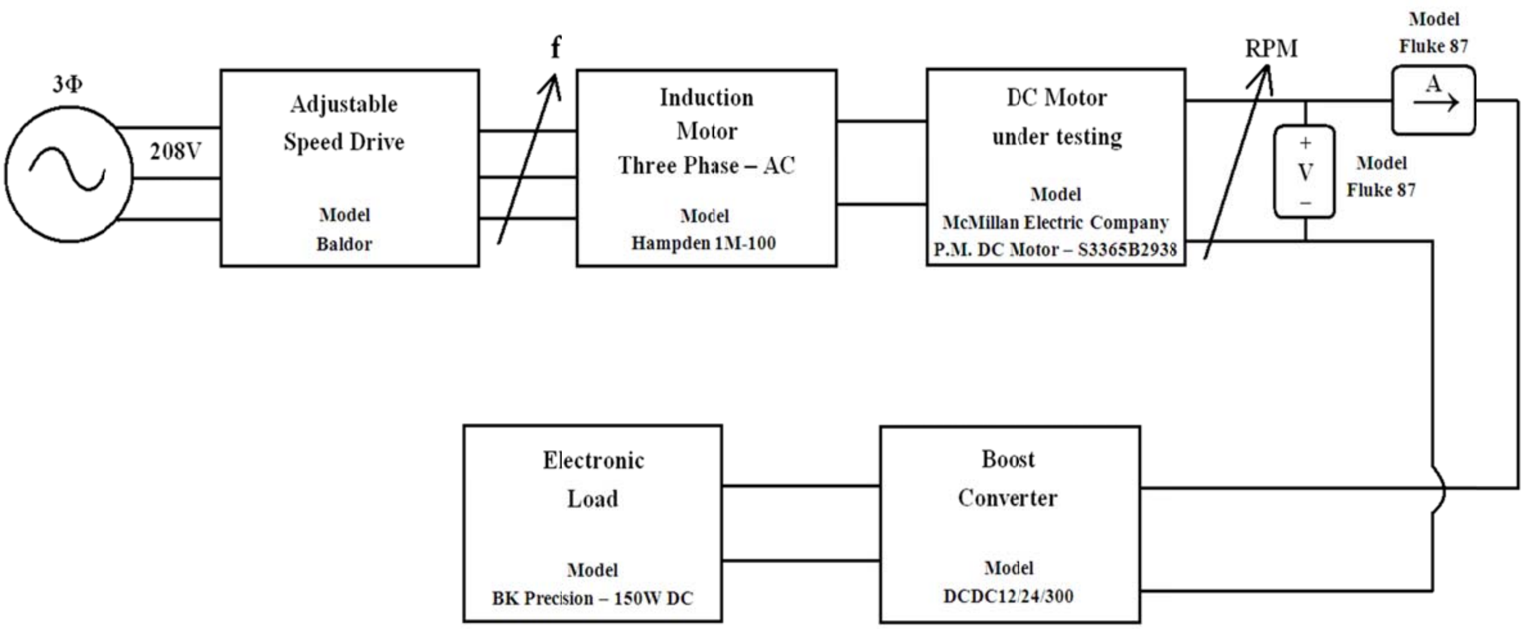


Figure 5-2: Block Diagram Complete Test Plan interface of all components

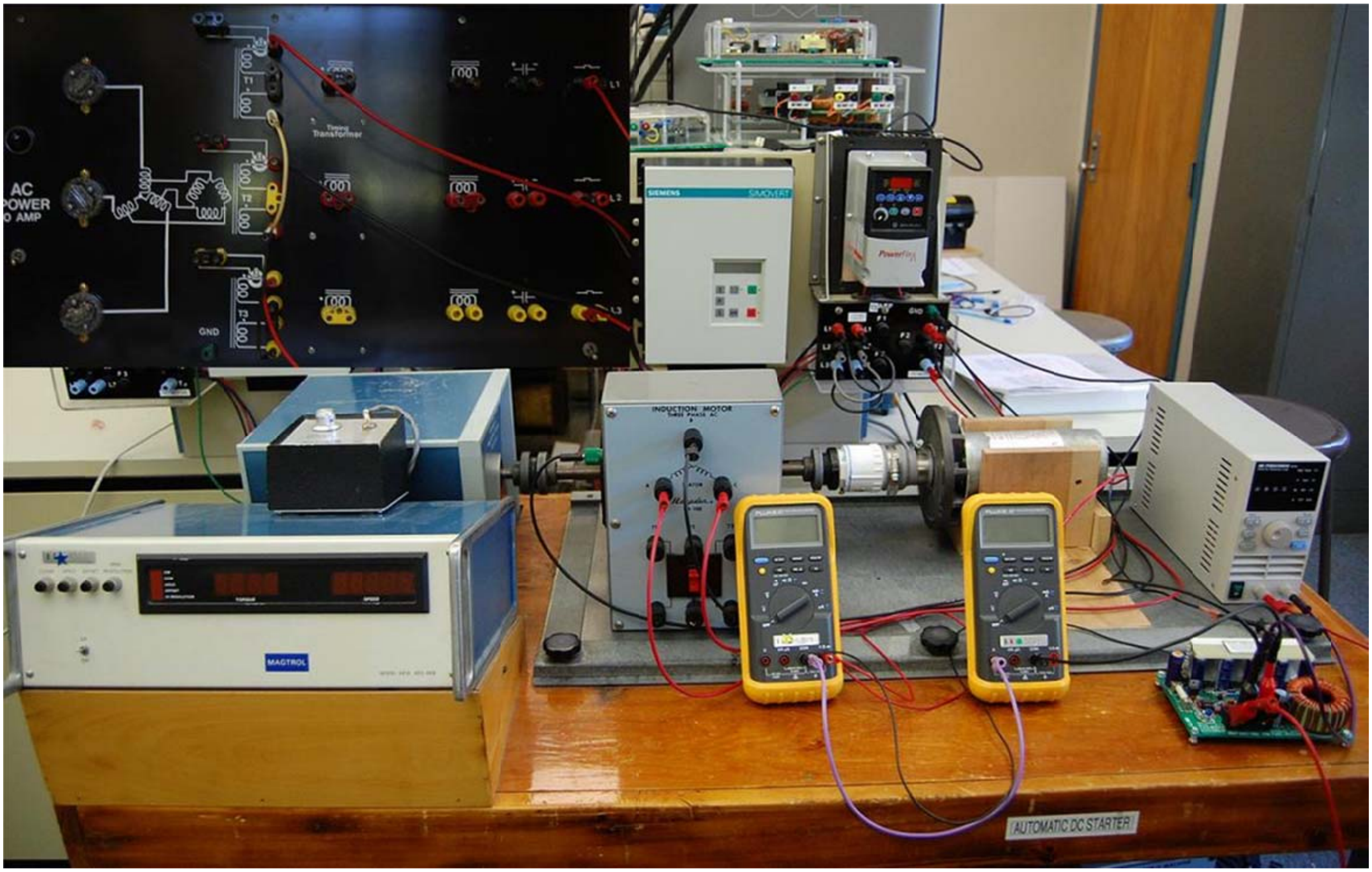


Figure 5-3: Physical Image of Complete Test Plan interface of all components

Once all of these components are interfaced, the output of this system will be monitored. The DC motor will be set at the speed that allows the boost converter to generate 24V under no load. Under the same speed, the electronic load will then be used to control the amount of current drawn at the output. The load will then be increased and continued to do so until the output voltage drops below 2.5% of what is desired. The output current and power at this point will resemble their maximums at the given speed. The same steps will be done at different speeds, ideally from 150RPM to 600RPM. RPMs below 150 and above 600 are neglected because these speeds will produce an output voltage from the motor that is too low to activate the boost converter or are rotational speeds that are too high for typical wind speeds to generate, respectively.

Chapter VI. Development and Construction

There are many components that will be used to implement this project and each of them needs to be properly connected to avoid damaging of any of the machines and equipment. Testing will be done in a lab that has access to a three phase power system. The three phase system will be configured in a wye-connection that will provide a line-to-line voltage of 208V to energize the adjustable speed drive. Resistive leads are used to connect the AC power to the adjustable speed drive to an induction motor. Figure 6-1 shows the adjustable speed drive that is going to be used when conducting our tests.

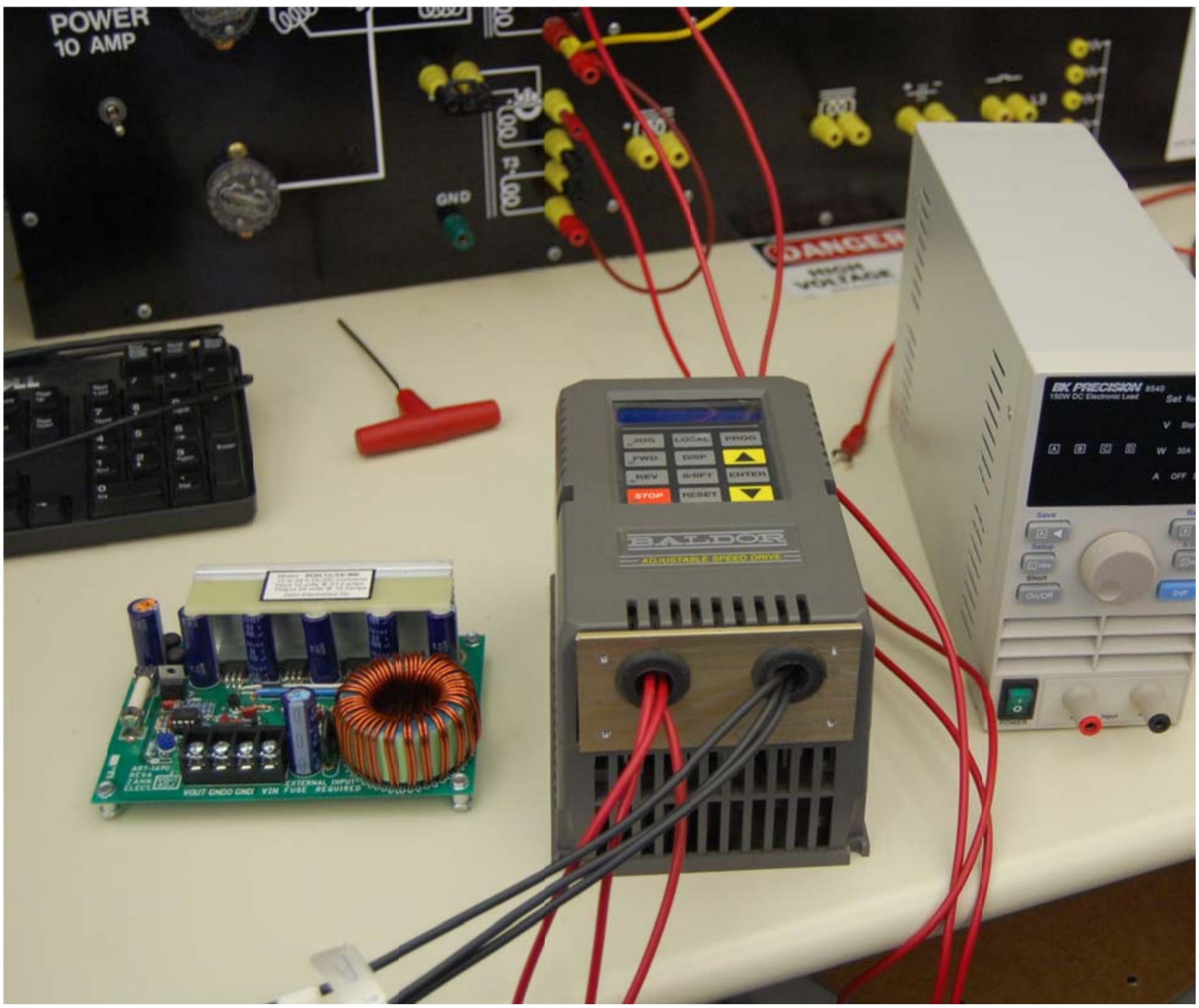


Figure 6-1: Interface between the AC power supply (back, black wall) and adjustable speed drive (middle, gray box). Also in circuit is the DC-DC converter (left board) and power load (right machine).

In order to test the proposed system, the DC motor has to be coupled to a prebuilt motor, which is also attached to a dynamometer set up from the machines lab. In this particular set up, the induction motor is mounted onto a metal platform stand. This means that the permanent magnet motor must also be mounted on a stand of the appropriate height and size to allow it to align with the induction motor. Figure 6-2 depicts the set up.

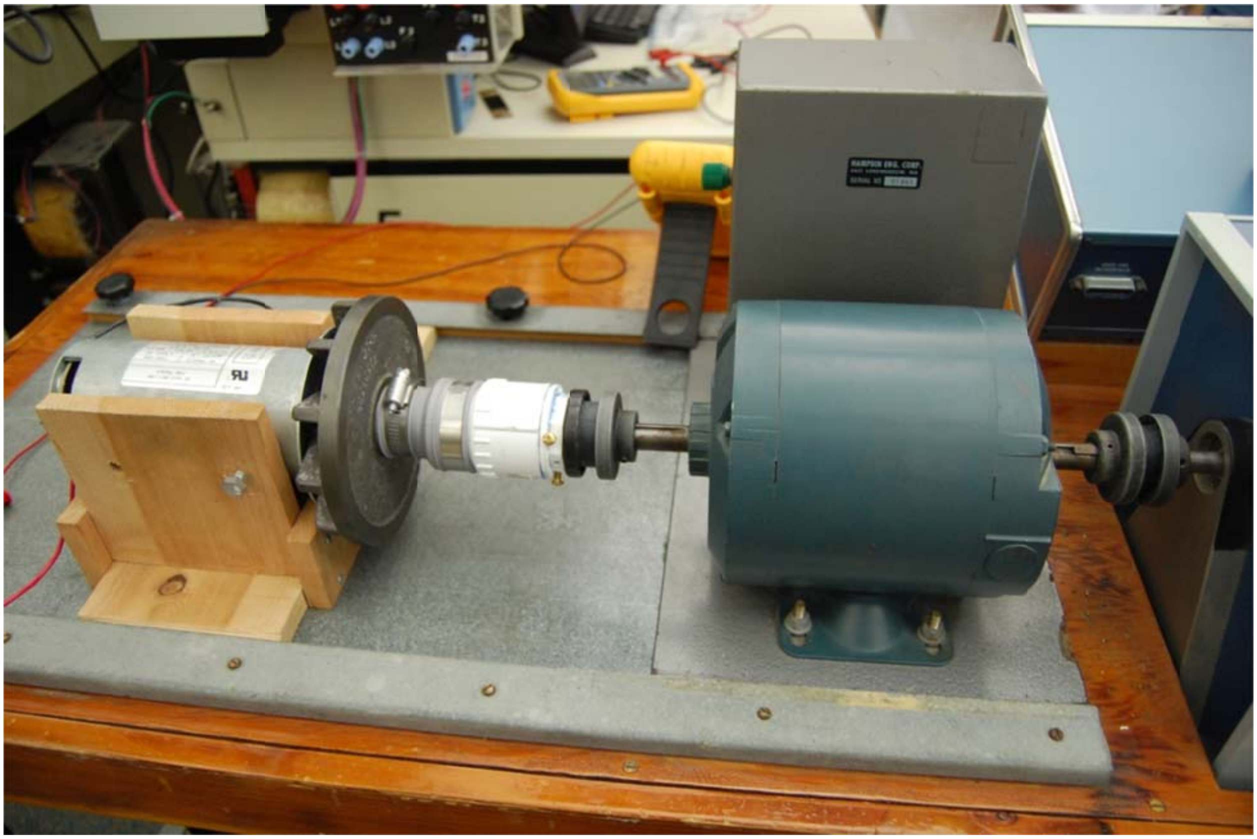


Figure 6-2: Interface between permanent magnet motor (left) and the induction motor (right). Customized coupling is the part that connects the two machines.

The stand for the permanent magnet motor needs to be built in a way that will raise the center of the motor to be approximately 4 inches tall to connect with the induction motor. There also needs to be a base for the stand to safely fasten it to a cart to ensure that the motor and stand do not move during testing. The base needs to be approximately 14 inches long with slightly less than ½ inch thickness in order for it to be held by metal clamps on the sides as shown in Figure 6-3 on the next page.

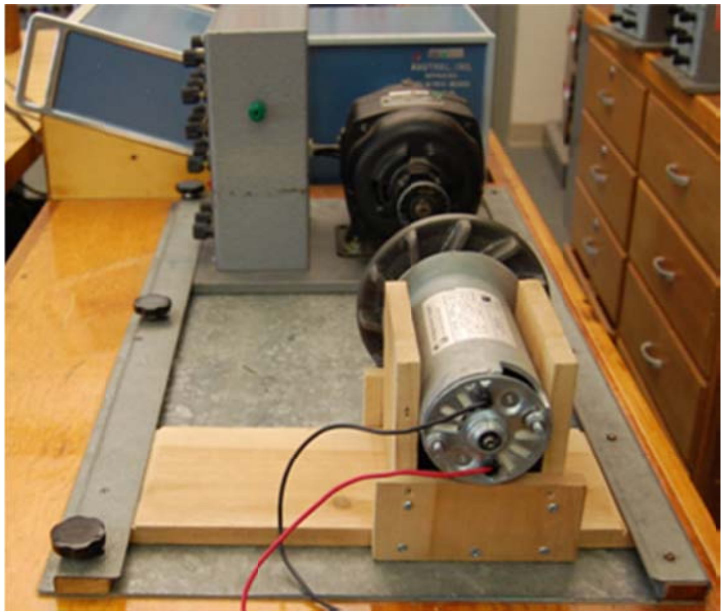


Figure 6-3: Picture of the metal clamps that lock the base of the stand in place.

For the permanent magnet motor to be directly aligned to the induction motor, the stand will need to be positioned in a way that will have the center of the permanent magnet motor to be about 4 ½ inches from one side of the base. The stand also needs to be built in a way that will securely fasten the permanent magnet motor, preventing it from moving off of the stand.

Also to connect the permanent magnet motor to the induction motor, a customized coupling connection must be made that can link the permanent magnet motor to the induction motor. The coupling is made from a flexible adaptor that is tightly wrapped around the rotator of the permanent magnet motor and a PVC plug. The plug is then used to hold and screw a grooved metal onto the coupling that will connect to another grooved metal on the induction motor. A connection must also be made between the permanent magnet motor and the DC-DC boost converter with the use of resistive leads. All loads connected to the output of the converter are also linked via resistive leads. There will also be two multi-meters connected to the output of the permanent magnet motor to measure the voltage and current that the motor is generating to the converter.

Chapter VII. Integration and Test Results

In the test plans section, three set ups were presented to help identify the properties of the motor, converter, and the two components combined. For the no load test of the converter, the output voltage of the DC motor can generate between 10.66V to 19.65V from the RPM speeds of 299 to 551. These results, displayed in Table 7-1 and Figure 7-1, show that the motor at low to medium speeds can provide enough voltage for the boost converter to turn on.

Table 7-1: Results from the no load test of the DC Motor

RPM	V (V)
52	1.82
99	3.52
148	5.3
201	7.16
248	8.85
299	10.66
353	12.59
403	14.4
451	16.11
503	17.91
551	19.65
601	21.44
658	23.47
699	24.96
750	26.77
800	28.58
850	30.39

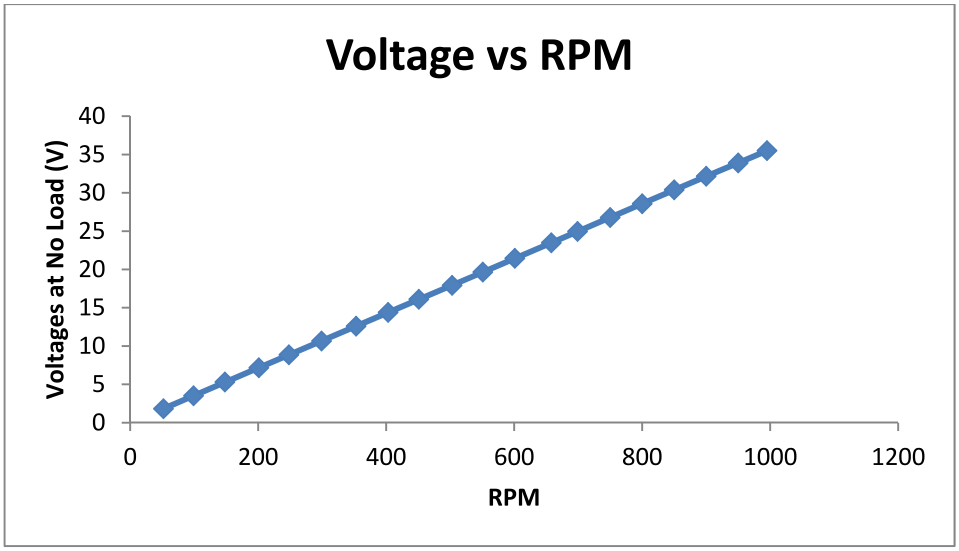


Figure 7-1: Plot showing the relationship between voltage and speed at with no load connect to the motor.

The input range of the Zahn boost converter was also tested. The stated input voltage range of 10-20Vwas tested using a DC power supply. Conducting this experiment, we found that the input voltage range to obtain 24V output is between 11.2V to 24V initially, and after the converter is activated, the input voltage can be turned down to as low as 3.7V and still maintain 24V output. In addition, the converter was also put through a load test. It is desired to output 100W, so the full load output current needed to produce this power output with a 24V output voltage is 4.17A. While maintaining a constant input voltage of 12V, an increment of 0.417A was done to the load to obtain data showing 10% augmentations of each test. When the boost converter reaches full load, we noticed that a lot of current from the source is being pulled in order to achieve close to 100W output. The efficiency of the converter is not what is stated in the company's website; however 89% efficiency is still very efficient and effective in not having too much lost between the input and output. Table 7-2 displays the results of different loads on the converter. Figure 7-2 shows the efficiency of the converter while undergoing various load tests.

Table 7-2: Results from the Boost Converter undergoing load tests.

Vin	Iin	Vout	Iout	Pout	Pin	% Efficiency
12	0.987	23.96	0.417	9.99	11.84	84.36
12	1.854	23.95	0.834	19.97	22.25	89.78
12	2.679	23.9	1.251	29.90	32.15	93.00
12	3.662	23.9	1.668	39.87	43.94	90.72
12	4.609	23.87	2.085	49.77	55.31	89.99
12	5.555	23.85	2.502	59.67	66.66	89.52
12	6.497	23.82	2.919	69.53	77.96	89.18
12	7.46	23.79	3.336	79.36	89.52	88.65
12	8.327	23.76	3.753	89.17	99.92	89.24
12	9.343	23.72	4.17	98.91	112.12	88.22

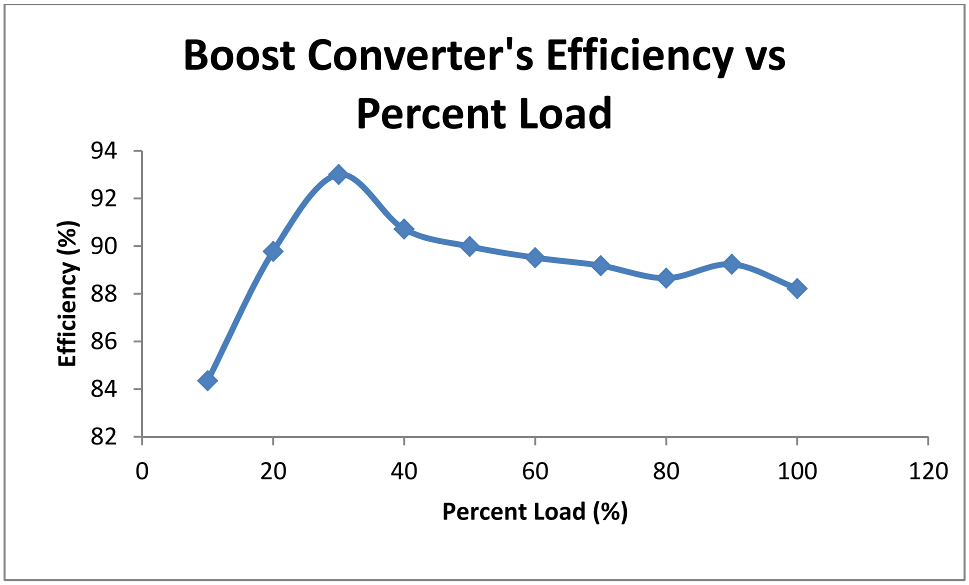


Figure 7-2: Plot of the boost converter's efficiency while undergoing various load tests.

In addition to finding the converter’s efficiency, it is also important to find its load and line regulation as each of these will allow us to tell how the converter can maintain its output voltage when its output power fluctuates or when the input voltage varies while the converter is performing at max load, respectively. The following two equations are used to find load and line regulation:

$$\%\ Load\ Regulation = \frac{V_{out(low-load)} - V_{out(high-load)}}{V_{out(high-load)}}\ x\ 100\% \quad (1)$$

$$\%\ Line\ Regulation = \frac{V_{out(high-input)} - V_{out(low-input)}}{V_{out(nominal)}}\ x\ 100\% \quad (2)$$

Extracting the data from Table 7-2 when the converter is performing at 10% and 100% loads, the load regulation of Zahn’s Boost Converter is 9.97% which is pretty good as this means the output voltage does not vary too much when we are demanding more power from the converter. The value of 9.97% for the percent load regulation was found by obtaining output voltages of 24.26V at no load and 22.06V at 96% of max load when maintaining a constant input voltage of 12.22V. The line regulation of the boost converter is determined to be 31.57% for the difference in output voltage when the input voltage reaches its upper and lower limitations before the output voltage becomes unstable. 10V and 20V were used as the lower and upper bounds of the input voltage range because those are the recommended voltage limits of the Zahn’s Boost Converter. The converter outputted 15.66V and 22.67V when receiving 10V and 20V at the input, respectively, and the nominal voltage output was around 22.2V. The nominal voltage output of the converter should be 24V but the converter could only output a stable 22.2V due to the converter operating at maximum load of 12.5A, which will provide a lot of strain to the converter.

After testing the converter and the motor individually, they need to be connected together for further testing. An adjustable speed drive was used to control the motor's speed while the electronic load controlled the load at the output of the converter. Load tests were done at speeds from 150RPM to 600RPM to determine the peak output current and power for the two interfaced systems. It is important to note that the motor needed to first be driven at 350RPM to charge the boost converter before data between 150RPM to 350RPM became valid and able to output 24V.

In each RPM case, 150RPM to 600RPM in increments of 50RPM, we noticed that the system was most efficient at the maximum output current the boost converter can load while still maintaining 24V on the output. Each case obtained its max output current and power at different input voltages into the boost converter. The next sets of tables will provide values of the input/output voltages, currents, and powers, and the system's efficiency at specified RPMs. It is important to note that as the load increases, it demands more current and output power out of the motor causing the speed of the machine to slow down. When the speed of the RPM decreases by about 30RPM compared to the initial RPM at no load, the boost converter is no longer able to output 24V.

Table 7-3: System results at 150RPM, after initially running the DC Motor at 350RPM

V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{in} (W)	% Efficiency
3.62	*0.279*	*23.90*	*0.000*	*0.000*	*1.010*	*0.00*
3.36	0.318	21.35	0.009	0.192	1.068	17.98
3.20	0.351	18.85	0.019	0.358	1.123	31.89

At a low 150RPM, the motor doesn't maintain 24V output voltage when a load is applied, making the system inefficient at low speeds. At 0.216% of full load (0.216% of 4.17A), the output voltage is at 21.35V at a dismal 17.98% efficiency.

Table 7-4: System results at 208RPM, after initially running the DC Motor at 350RPM

V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{in} (W)	% Efficiency
6.10	0.202	24.01	0.000	0.000	1.232	0.000
5.85	0.248	24.00	0.010	0.240	1.451	16.543
5.55	0.297	24.00	0.020	0.480	1.648	29.120
5.25	0.362	23.99	0.030	0.720	1.901	37.869
4.86	0.437	23.99	0.040	0.960	2.124	45.183
4.26	0.551	23.99	0.050	1.200	2.347	51.102
4.16	*0.572*	*23.98*	*0.051*	*1.223*	*2.380*	*51.396*
4.14	0.579	23.84	0.052	1.240	2.397	51.717
4.06	0.590	23.41	0.055	1.288	2.395	53.751
3.96	0.620	22.79	0.060	1.367	2.455	55.694
3.47	0.640	20.42	0.066	1.348	2.221	60.686
3.44	0.658	20.00	0.070	1.400	2.264	61.851

At 208RPM, the maximum output current is 0.051A, 1.22% of full load. The efficiency is improved over the previous motor's speed of 150RPM. When the load is slightly increased to 0.052A, the RPM dropped from the initial no load speed of 208 down to 203RPM.

Table 7-5: System results at 255RPM, after initially running the DC Motor at 350RPM

V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{in} (W)	% Efficiency
8.05	0.176	24.01	0.000	0.000	1.417	0.000
7.64	0.246	24.00	0.020	0.480	1.879	25.540
7.23	0.323	24.00	0.040	0.960	2.335	41.108
6.76	0.412	23.99	0.060	1.439	2.785	51.682
6.22	0.521	23.99	0.080	1.919	3.241	59.223
5.44	0.684	23.99	0.100	2.399	3.721	64.473
4.74	0.850	23.99	0.110	2.639	4.029	65.498
4.32	*0.945*	*23.99*	*0.114*	*2.735*	*4.082*	*66.991*
4.10	0.984	23.10	0.120	2.772	4.034	68.709
3.68	1.033	21.20	0.130	2.756	3.801	72.499
3.50	1.083	19.95	0.140	2.793	3.791	73.684
3.30	1.140	18.73	0.150	2.810	3.762	74.681

For Table 7-5, at the initial 255RPM setting, the maximum output power and current is 2.74W and 0.114A, respectively. The output-input power ratio efficiency is still not as desirable as we would like at 67%. At this point, the DC motor's speed also drops slightly from 255RPM to 249RPM. Another note is that even though the efficiency and output power increase after the output voltage drops less than 24V, it is not desirable due to the goal of maintaining 24V while increasing output power.

Table 2-6: System results at 310RPM, after initially running the DC Motor at 350RPM

V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{in} (W)	% Efficiency
10.10	0.151	24.01	0.000	0.000	1.525	0.000
9.75	0.206	24.01	0.020	0.480	2.009	23.908
9.43	0.263	24.01	0.040	0.960	2.480	38.724
9.09	0.326	24.00	0.060	1.440	2.963	48.594
8.76	0.392	24.00	0.080	1.920	3.434	55.913
8.40	0.464	24.00	0.100	2.400	3.898	61.576
8.00	0.543	24.00	0.120	2.880	4.344	66.298
7.59	0.635	23.99	0.140	3.359	4.820	69.686
7.05	0.755	23.99	0.160	3.838	5.323	72.113
6.33	0.919	23.99	0.180	4.318	5.817	74.231
6.00	*1.000*	*23.98*	*0.189*	*4.532*	*6.000*	*75.537*
4.34	1.413	23.95	0.190	4.551	6.125	74.290
3.72	1.450	21.25	0.200	4.250	5.394	78.791
3.41	1.560	19.05	0.220	4.191	5.320	78.784
3.04	1.680	16.83	0.240	4.039	5.107	79.088
2.69	1.770	14.50	0.260	3.770	4.761	79.180

When the motor is running at 310RPM, the system is able to achieve higher output power as expected compared to the previous speeds. However, like its previous speeds, the motor needs to be initially run at 350RPM in order to achieve 24V output from the converter. The output power at this speed is also too low compared to the scope of this project with the maximum output current at 0.189A and power at 4.53W. The speed at this point drops to 299RPM.

Once the speed of 350RPM and above is set, the converter no longer needs to be initially started to maintain 24V output at no load. The next set of tables shows the characteristics of the system at each speed. The efficiency for each speed is increased due to its increase in output power and current. Also, at each maximum point, the RPM of the motor drops to around 30RPM compared to the initial no load RPM. At 600RPM, the maximum power we were able to get from the load and boost converter is 23.66W at 23.7% of the full load. Note that each italicized row for each speed represents maximum output current and power before the output voltage drops below the desired 24V.

Table 7-7: System Results at 358RPM

V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{in} (W)	% Efficiency
11.99	0.130	24.03	0.000	0.000	1.559	0.000
11.69	0.177	24.02	0.020	0.480	2.069	23.217
11.40	0.223	24.02	0.040	0.961	2.542	37.794
11.14	0.272	24.01	0.060	1.441	3.030	47.543
10.86	0.323	24.01	0.080	1.921	3.508	54.758
10.55	0.378	24.01	0.100	2.401	3.988	60.207
10.28	0.435	24.01	0.120	2.881	4.472	64.430
10.00	0.494	24.00	0.140	3.360	4.940	68.016
9.66	0.561	24.00	0.160	3.840	5.419	70.858
9.33	0.633	24.00	0.180	4.320	5.906	73.147
8.97	0.713	23.99	0.200	4.798	6.396	75.020
8.56	0.807	23.99	0.220	5.278	6.908	76.402
8.13	0.914	23.99	0.240	5.758	7.431	77.483
7.54	1.052	23.98	0.260	6.235	7.932	78.602
7.26	1.127	23.98	0.270	6.475	8.182	79.132
6.74	*1.250*	*23.97*	*0.279*	*6.688*	*8.425*	*79.378*
4.04	1.943	21.54	0.280	6.031	7.850	76.833
3.61	2.040	19.99	0.300	5.997	7.364	81.432
3.31	2.150	17.95	0.320	5.744	7.117	80.714
2.95	2.260	15.70	0.340	5.338	6.667	80.066
2.59	2.370	13.55	0.360	4.878	6.138	79.468

Table 7-8: System Results at 406RPM. *Note: at 9.20W the motor's RPM drops to 385.*

V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{in} (W)	% Efficiency
13.79	0.110	24.04	0.000	0.000	1.517	0.000
13.28	0.191	24.02	0.040	0.961	2.536	37.879
12.81	0.274	24.02	0.080	1.922	3.510	54.747
12.33	0.364	24.01	0.120	2.881	4.488	64.196
11.85	0.462	24.01	0.160	3.842	5.475	70.170
11.33	0.570	24.00	0.200	4.800	6.458	74.325
10.78	0.689	24.00	0.240	5.760	7.427	77.550
10.13	0.832	23.98	0.280	6.714	8.428	79.666
9.44	1.000	23.98	0.320	7.674	9.440	81.288
8.48	1.240	23.97	0.360	8.629	10.515	82.064
8.05	1.368	23.97	0.379	9.085	11.012	82.495
8.00	*1.390*	*23.97*	*0.384*	*9.204*	*11.120*	*82.774*
7.84	1.449	23.97	0.389	9.324	11.360	82.079
3.57	2.650	19.10	0.400	7.640	9.461	80.757
3.41	2.690	18.00	0.410	7.380	9.173	80.454
3.03	2.810	15.70	0.430	6.751	8.514	79.290

Table 7-9: System Result at 448RPM. *Note: At maximum points, RPM drops to 425RPM.*

V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{in} (W)	% Efficiency
15.40	0.094	24.05	0.000	0.000	1.448	0.000
14.96	0.164	24.03	0.040	0.961	2.453	39.178
14.56	0.236	24.02	0.080	1.922	3.436	55.923
14.15	0.313	24.02	0.120	2.882	4.429	65.081
13.73	0.394	24.02	0.160	3.843	5.410	71.044
13.30	0.480	24.01	0.200	4.802	6.384	75.219
12.88	0.573	24.01	0.241	5.786	7.380	78.404
12.40	0.674	23.99	0.280	6.717	8.358	80.372
11.90	0.788	23.99	0.320	7.677	9.377	81.867
11.41	0.914	23.98	0.360	8.633	10.429	82.779
10.78	1.060	23.98	0.400	9.592	11.427	83.943
10.08	1.238	23.97	0.441	10.571	12.479	84.708
9.40	1.450	23.96	0.469	11.237	13.630	82.445
9.11	1.500	23.96	0.475	11.381	13.665	83.286
9.07	1.490	23.97	0.481	11.530	13.514	85.314
8.80	*1.600*	*23.96*	*0.490*	*11.740*	*14.080*	*83.384*
3.02	3.230	15.70	0.500	7.850	9.755	80.475
2.52	3.400	12.00	0.540	6.480	8.568	75.630
2.34	3.460	10.70	0.560	5.992	8.096	74.008

Table 7-10: System Result at 508RPM. *Note: At maximum points, speed drops to 471RPM.*

V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{in} (W)	% Efficiency
17.63	0.073	24.06	0.000	0.000	1.287	0.000
17.15	0.147	24.04	0.050	1.202	2.521	47.679
16.69	0.226	24.03	0.099	2.379	3.772	63.070
16.21	0.309	24.03	0.149	3.580	5.009	71.482
15.78	0.398	24.02	0.200	4.804	6.280	76.491
15.33	0.490	24.01	0.249	5.978	7.512	79.589
14.89	0.589	24.00	0.299	7.176	8.770	81.822
14.40	0.694	24.00	0.350	8.400	9.994	84.054
13.88	0.813	23.99	0.399	9.572	11.284	84.825
13.37	0.939	23.98	0.449	10.767	12.554	85.763
12.82	1.081	23.98	0.501	12.014	13.858	86.691
12.20	1.244	23.97	0.550	13.184	15.177	86.866
11.44	1.441	23.96	0.600	14.376	16.485	87.206
10.40	1.725	23.95	0.650	15.568	17.940	86.775
10.35	1.770	23.95	0.660	15.807	18.320	86.285
10.30	*1.820*	*23.95*	*0.663*	*15.879*	*18.746*	*84.705*
2.67	4.040	10.50	0.670	7.035	10.787	65.219
2.50	4.030	10.20	0.680	6.936	10.075	68.844

Table 7-11: System Result at 548RPM. *Note: At maximum points, RPM drops to 515.*

V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{in} (W)	% Efficiency
19.16	0.059	24.06	0.000	0.000	1.130	0.000
18.69	0.127	24.05	0.050	1.203	2.374	50.661
18.28	0.197	24.04	0.099	2.380	3.601	66.089
17.86	0.271	24.04	0.149	3.582	4.840	74.007
17.45	0.350	24.03	0.200	4.806	6.108	78.690
17.08	0.430	24.02	0.249	5.981	7.344	81.436
16.67	0.516	24.01	0.299	7.179	8.602	83.460
16.24	0.606	24.00	0.350	8.400	9.841	85.353
15.80	0.704	24.00	0.400	9.600	11.123	86.306
15.33	0.808	24.00	0.449	10.776	12.387	86.997
14.85	0.922	23.98	0.500	11.990	13.692	87.571
14.35	1.044	23.97	0.549	13.160	14.981	87.839
13.84	1.176	23.97	0.599	14.358	16.276	88.217
13.22	1.327	23.96	0.649	15.550	17.543	88.640
12.65	1.497	23.95	0.699	16.741	18.937	88.404
11.65	1.760	23.95	0.749	17.939	20.504	87.488
11.36	1.869	23.94	0.769	18.410	21.232	86.709
11.30	1.900	23.95	0.779	18.657	21.470	86.898
11.25	*1.920*	*23.95*	*0.784*	*18.777*	*21.600*	*86.930*
2.75	4.390	10.50	0.790	8.295	12.073	68.710
2.80	4.380	10.40	0.800	8.320	12.264	67.841
2.93	4.320	10.40	0.820	8.528	12.658	67.375

Table 7-12: System Result at 598RPM. *Note: At maximum output current and power, speed drop to 565RPM.*

V_{in} (V)	I_{in} (A)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{in} (W)	% Efficiency
21.06	0.044	24.07	0.000	0.000	0.927	0.000
20.32	0.167	24.05	0.099	2.381	3.393	70.163
19.61	0.300	24.03	0.200	4.806	5.883	81.693
18.90	0.445	24.02	0.299	7.182	8.411	85.393
18.16	0.602	24.01	0.399	9.580	10.932	87.630
17.36	0.778	23.99	0.500	11.995	13.506	88.812
16.54	0.971	23.98	0.599	14.364	16.060	89.438
15.63	1.199	23.96	0.699	16.748	18.740	89.369
14.89	1.395	23.96	0.769	18.425	20.772	88.704
14.59	1.479	23.95	0.799	19.136	21.579	88.681
13.50	1.780	23.94	0.889	21.283	24.030	88.567
12.88	1.956	23.93	0.929	22.231	25.193	88.242
12.50	2.063	23.93	0.949	22.710	25.788	88.064
12.60	2.039	23.93	0.960	22.973	25.691	89.418
12.30	2.144	23.92	0.975	23.322	26.371	88.437
12.00	2.215	23.92	0.985	23.561	26.580	88.643
11.90	*2.260*	*23.92*	*0.989*	*23.657*	*26.894*	*87.963*
3.31	4.750	10.40	0.990	10.296	15.723	65.486
3.35	4.720	10.40	1.000	10.400	15.812	65.773
3.46	4.670	10.40	1.020	10.608	16.158	65.651

The following figure shows a graph of all the voltage and output characteristics at different speeds. From Figure 7-3, it is clear that the higher RPM the motor spins the more current it will be able to provide for the load. Also, the 24V output from the boost converter stays the same up until the load demands about 0.989A, which is about 23.72% of full load. After the point where the converter is unable to provide 24V due to the current demands of the load, the output voltage drops drastically to about 10V. From this graph, the system may not be able to provide enough voltage and current to more demanding loads which will be something to consider for the scope of this project.

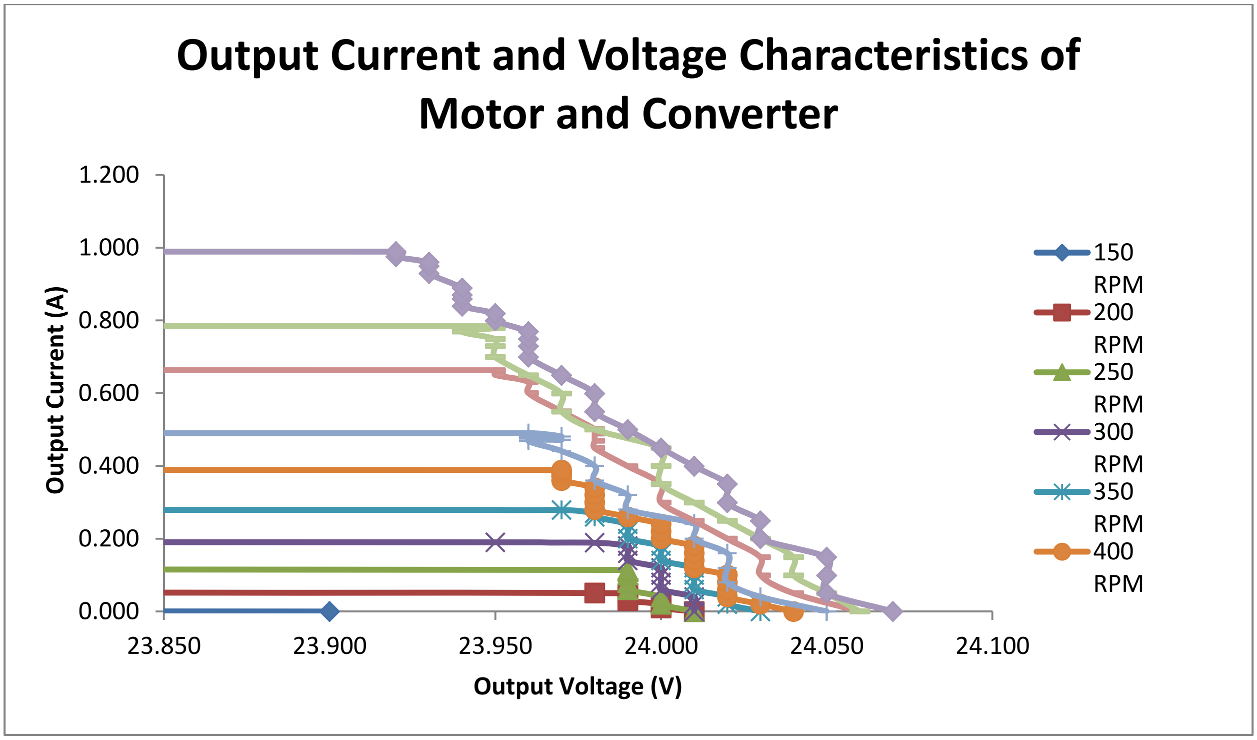


Figure 7-3: Graph displaying output voltage and current characteristics of the tested system.

Figure 7-4, displays the maximum output current delivered to the load while maintaining 24V output at various speeds. As expected, the faster the motor turns the more current will be generated and delivered to the load.

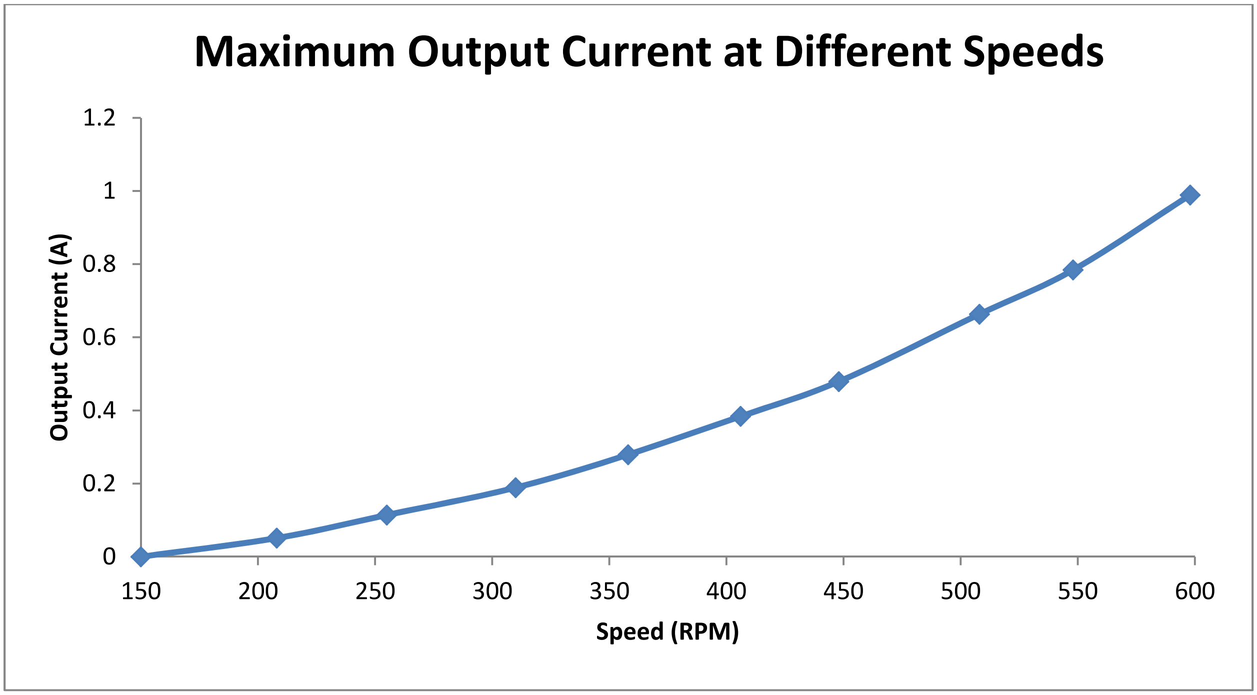


Figure 7-4: Graph displaying maximum output current at different speeds.

The next figure shows the output power relationship with various motor speeds. The relationship between the two is the same as the output current and speed graph shown in Figure 7-4. This is because power relies on both voltage and current, and since the desired output voltage remains at 24V, the power will increase by the same amount current increases.

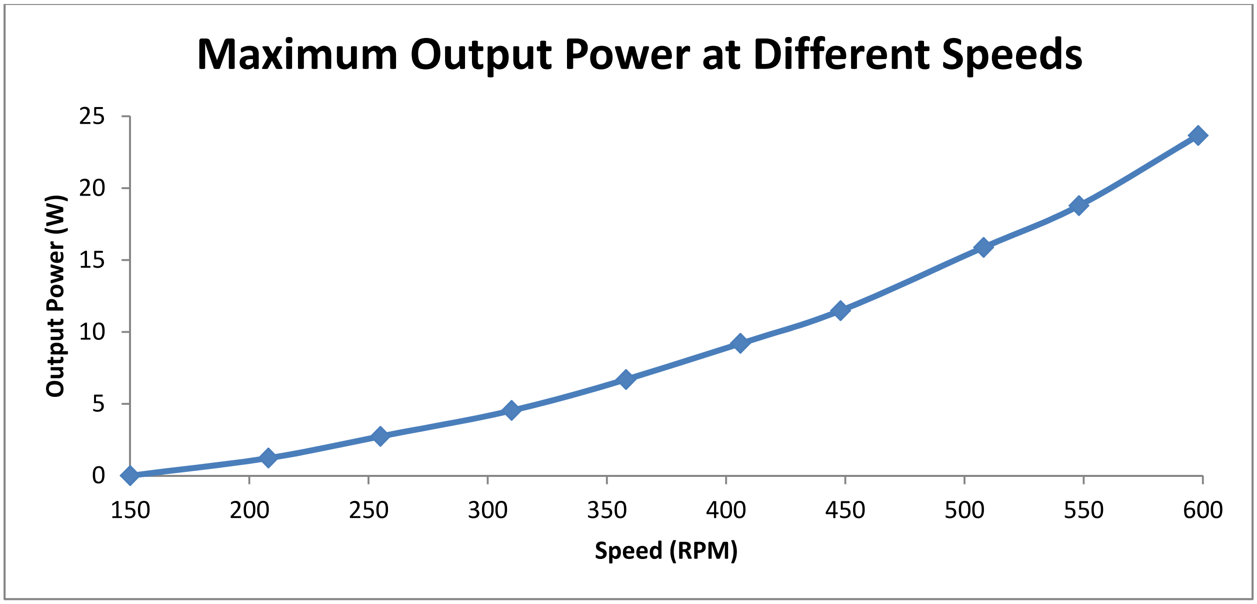


Figure 7-5: Graph displaying maximum output power at different speeds.

Figure 7-6 shows that as speed increases, efficiency of the system also increases at various loads. The efficiency data points were extracted from each maximum current and power set at different speeds. After the vast increase in efficiency between 150RPM and 350RPM, the efficiency begins to saturate. The efficiency will saturate around 88%, close to the boost converter's rated efficiency. It is also important to note that between 150RPM and 350RPM, the converter needs to be initially charged at 350RPM in order to output 24V.

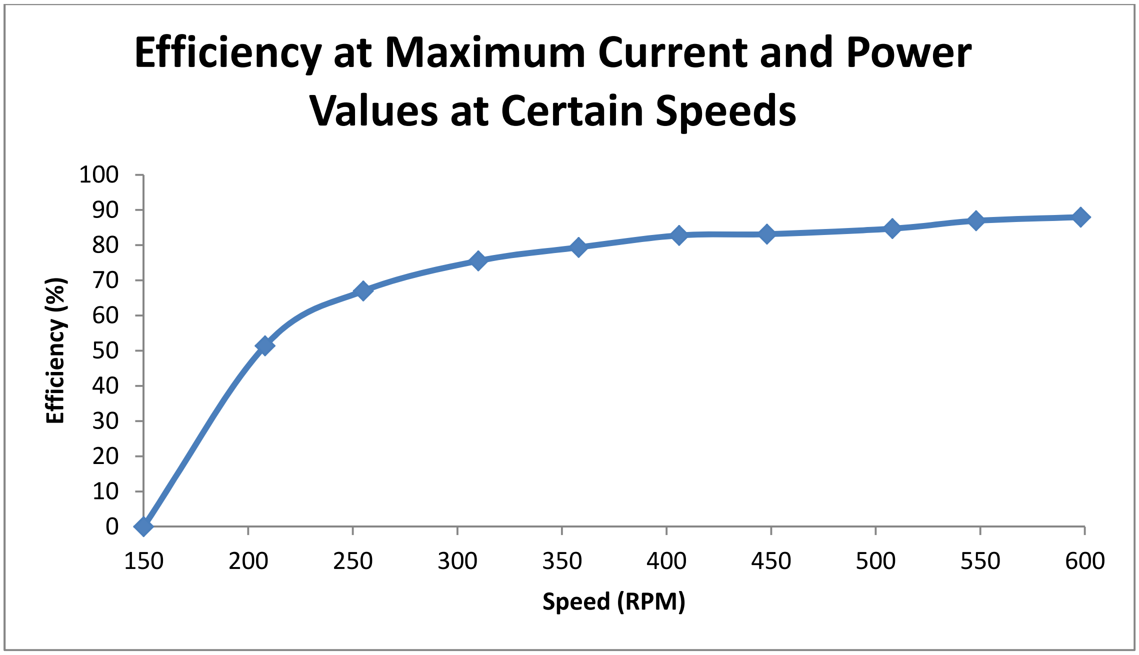


Figure 7-6: Graph showing increase in efficiency as speed of the DC motor increases.

Since load varies, maximum output power will also vary at different RPM speeds. The next figure displays the efficiency of our proposed system at different RPM speeds and output power. We can see from Figure 7-7 that efficiency saturates at around 85% after the generator begins to output 5W. Also, the maximum output power is obtained as RPM is increased. It is important to note that at the end of each point at different RPM speeds, the output power vastly drops due to a great drop from the DC motor's input voltage to the boost converter, thus causing the boost converter to malfunction.

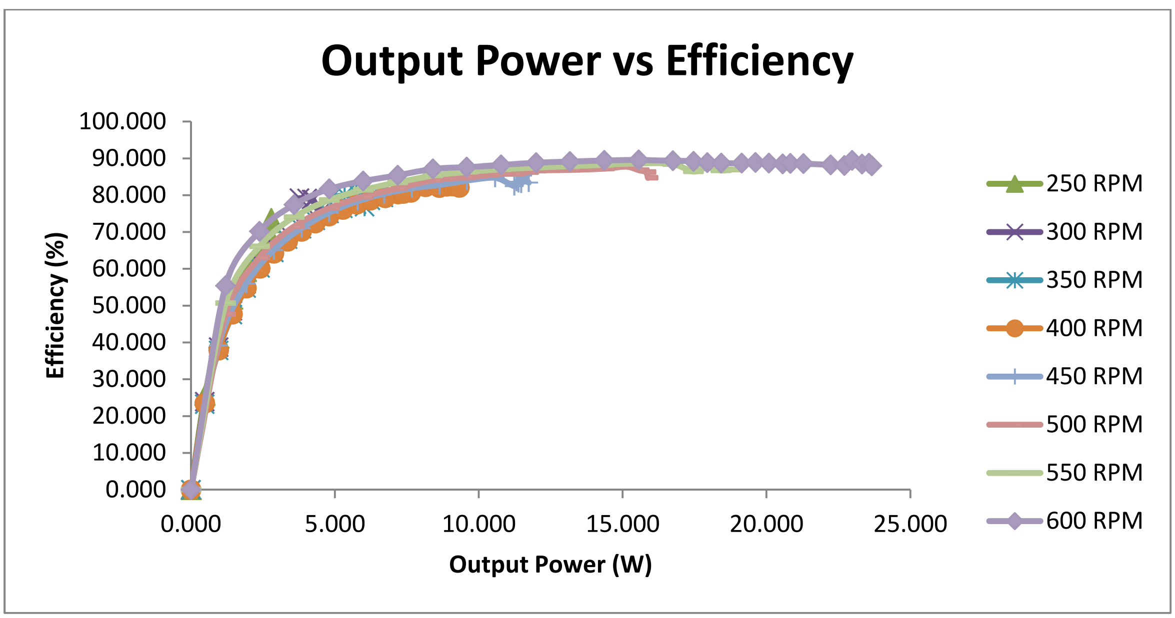


Figure 7-7: Plot showing output power and efficiency of the proposed system at various speeds.

Chapter VIII. Conclusion

Based on the data that we obtained, we have concluded that as the amount of load in the circuit increases, the initial RPM speed of the motor will decrease. This, therefore, states that more wind speed must be applied at the input in order for the motor to maintain the same amount of RPM speed at various amounts of load. However, when we applied more wind to take into account of the increase in load, we discovered that our output power only increased by about 1-2W between 350 to 600RPM. There may be a wider range in output power at higher speeds above 600 RPM, but our proposed system will never reach speeds of that magnitude.

Due to the focus of this project being towards third world countries, we wanted our proposed design to be cost efficient. Before considering the length and style of wind blades, we wanted to focus more towards the heart of the system, which is the motor that will be generating the DC current and voltage, and the DC-DC converter that will be providing high output power and the consistent 24V to the DC house. The total cost to implement and test these two components is approximately $305.50. The other components prices, such as the DC power supply, torque machine, the induction motor, the BK Precision Electronic Load, and others mentioned in our "Test Plans" section were not listed as those equipment were readily available in the school labs. The following table shows a breakdown of the components and cost of our proposed system, including parts we needed to use to conduct our tests.

Table 8-1: List of parts used for the proposed system

Parts	Costs
McMillan P.M. Motor (*Ebay*)	115.00
Zahn Boost Converter (*Mann. Website*)	169.00
Custom Built Wood Stand (*Home Depot*)	15.00
PVC Plug (*Home Depot*)	1.21
Flexible Adapter (*Home Depot*)	0.95
Drain Connection (*Home Depot*)	4.29
Total	**305.45**

When we were conducting tests for our system, we encountered a few issues and difficulties. While testing our DC motor using a coupled induction motor, we found that the induction motor heats up quickly when applying more load to the system, causing the output voltage and current of the DC motor to slightly drop, thus effecting our overall data. One method we used in resolving this issue, however, was to use multiple induction motors and replacing the used induction motor after each speed test. This was possible due to the available amount of motors we had access to in lab. Another difficulty we came across was how to take into account of speed drop when load increases and how to increase output power to what is desired for the main purpose of this project. We resolved the speed problem by increasing the frequency from our variable speed drive machine whenever the RPM decreases from the initial speed, but we must take into account that more wind, in real application, will need to be applied should the load increase.

It has been determined through much consideration that it will be necessary to implement gears into this project. The gears will be necessary to create the amount of RPM speeds required from the motor when connected to loads since typical wind speeds will not be enough to obtain high output power. Before adding gears into the project, more research needs to be done to obtain a better understanding of its functions and how to interface it with the DC motor. If gears are included into the project, then the DC motor with the gears included need to be tested again to determine its new input voltage range. If this range is wider than what was considered in this project, then a new DC-DC converter needs to be researched. If the input voltage range falls in between 9-60V, the SynQor NQ60W60ETC10NRS-G could be considered.

If gears is not desired, then we suggest either purchasing a bigger, more expensive DC motor that can output higher amounts of current and still have high voltage-RPM ratio, or using an alternator. An alternator can generate electricity using the same principle as DC generators by using magnetic field around a conductor to induce current. Alternators also have an Automatic Voltage Regulator (AVR) that is used to control the current when maintaining a constant output voltage during various demands in load. An alternator is also accessible anywhere around the world since it is used in automotive vehicles to help charge the battery and power the electrical system in the engine of the vehicle. So to be cost efficient, alternators can be taken from the engine of vehicles in junk yards where non-operating vehicles are held and free parts can be taken from.

An adjustable height stand could also be considered for the final production of this project. It will add convenience and efficiency when obtaining optimal wind speeds for it can be adjusted for any location, and transported more easily.

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Appendix

A. Cost Estimates

Components	Cost
DC Permanent Magnet Motor	$115
DC – DC Converter	$169
Wood stand	$15
PVC Plug	$1.21
Flexible Adaptor	$0.95
Drain Conn	$4.29

Total cost: $305.45

B. Time Allocation